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Validation of the SATVIS Meteorological Range Estimation Model in the Northern Arabian Sea

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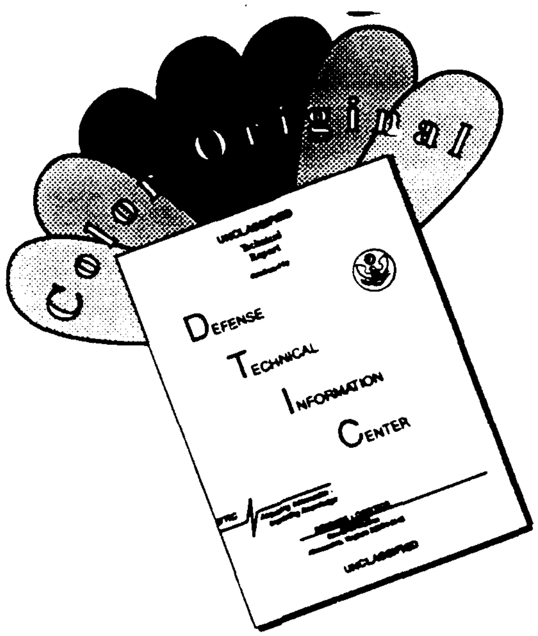

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ABSTRACT

The Navy's SATVIS Meteorological Range Estimation Model is evaluated utilizing a subset of Advanced Very High Resolution Radiometer (AVHRR) data over the northern Arabian Sea during October 1988 through May 1989. Variations in aerosol optical depth and the ratio between AVHRR channels 1 and 2 are observed and correlated with synoptic data. SATVIS meteorological ranges are compared with those determined using the Navy Aerosol Model. Sources of error are discussed in light of recent observations of the vertical distribution of aerosols in the troposphere. A qualitative assessment of SATVIS as a Navy Tactical Decision Aid (TDA) is attempted.

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1. INTRODUCTION

Variations in atmospheric extinction in the visible region of the electro-magnetic spectrum are heavily dependent on Mie scattering by atmospheric aerosols. Recent interest in the complex effect these aerosols have on the earth's climate system through their redistribution of solar and terrestrial radiation and their impact as condensation nuclei have led to the development of various remote sensing techniques in an effort to monitor data sparse regions. Satellite-based remote sensing techniques for measuring atmospheric optical properties resulting from variations in aerosol composition, concentration and distribution (e.g., Durkee et al., 1986; Griggs, 1979) lend themselves well to Navy tactical applications. These techniques have the potential to provide "over-the-horizon" meteorological range data which may be applied to aircraft-based and shipboard-based visibility forecasts and performance estimates for electro-optical sensors and weapons systems. In particular, the SATVIS model introduced by Haggerty et al. (1990) may be able to provide Navy tactical planners with near real-time measurements of aerosol optical depth and meteorological range over ocean surfaces using Advanced Very High Resolution Radiometer (AVHRR) data. The SATVIS model has undergone limited testing thus far, although preliminary results detailed by Haggerty et al. (1990) have been encouraging and have provided further impetus for the operational use of SATVIS and other satellite-

derived aerosol products such as those undergoing evaluation by the National Oceanic and Atmospheric Administration (NOAA) (Rao et al., 1989).

This report describes SATVIS meteorological ranges derived from AVHRR data over the northern Arabian Sea during the period from October 1988 through June 1989. Aerosol optical depth and the ratio between AVHRR channels 1 and 2 (a measure of the aerosol size distribution) are observed and correlated with synoptic data. For comparison, SATVIS meteorological range estimates are compared with the Navy Aerosol Model (Gathman (1983), which derives meteorological range from easily measured meteorological variables such as wind speed and relative humidity. Archived data from the Navy's Global Atmospheric Prediction System (NOGAPS) serve as input for the Navy Aerosol Model due to the lack of meteorological observations over the open ocean. Sources of error in SATVIS are discussed, and a qualitative assessment is made of the value of the SATVIS model to Navy tactical planners.

2. MODEL DESCRIPTION

a. SATVIS

The theoretical basis for the SATVIS aerosol optical depth model was illustrated by Durkee et al. (1986) and applied by Haggerty et al. (1990). For a cloud-free marine environment with small optical depth at visible wavelengths, the radiative transfer equation can be approximated by the

relationship

$$L_A = \frac{\omega_o F_o}{4\ \cos\ \theta}\, p(\psi_s)\ \tau_A \tag{1}$$

where LA is the upwelling radiance due to aerosol scattering, ω_0 is the single scattering albedo, F_0 is the solar radiative flux, θ is the satellite zenith angle, $p(\psi_s)$ is the scattering phase function with ψ being the scattering angle, and τ_A is the aerosol optical depth due to scattering. The Rayleigh scattering component of the upwelling radiance, being nearly constant, is estimated from pressure and temperature data and is removed from the upwelling radiance. The single scattering approximation assumes that the majority of scatterers in the clear air marine environment are hygroscopic, spherical marine aerosols so that the single scattering albedo is close to unity. Additionally, the solar radiative flux is assumed to be constant. Therefore, with a known satellite viewing geometry and phase function, the radiance received by the sensor will be linearly related to the aerosol optical depth. The SATVIS model developed by Haggerty et al. (1990) utilizes the aerosol optical depth obtained through the above radiative transfer principles to obtain an estimate of the aerosol extinction coefficient (β) using

$$\tau = \int_o^z \beta\,(z)\,dz \tag{2}$$

where z is height and Z is the top of the layer of interest. Due to the lack of information concerning the distribution of aerosols in the vertical, the model assumes that all aerosol extinction occurs within the boundary layer and that the extinction is constant within that layer. While this assumption may be reasonable for most well-mixed marine boundary layers with marine aerosols (Fairall et al., 1982), ongoing research suggests that the presence of aerosols of marine and/or continental origin above the marine boundary layer may be a significant source of error. The model also assumes a well-behaved aerosol size distribution, which is valid for most naturally occurring aerosols.

With the aerosol extinction coefficient, meteorological range as defined by Fenn et al. (1981) may be estimated using

$$\nu = \frac{3.9}{\beta} \qquad (3)$$

where υ is in units of km if β is in km^{-1}.

As mentioned previously, current research is revealing a greater presence o aerosols above the marine boundary layer than previously anticipated. The SATVIS model assumes that all aerosols are confined to this layer in the marine environment. In view of this, SATVIS meteorological range estimates were expected to be relatively lower than those obtained from the Navy Aerosol Model since aerosol extinction estimates from the satellite data probably include the effects of aerosols that may exist in the troposphere above the marine

boundary layer.

Hughes and Jensen (1988) demonstrated the ability to infer aerosol size distribution utilizing AVHRR channel 1 and ground-based infrared radiances. The SATVIS model utilizes a satellite-based multispectral technique initially introduced by Durkee (1984) to determine an aerosol size index that may be related to the scattering phase function. Specifically, the ratio of AVHRR channels 1 and 2 provides an indicator of the appropriate phase function to be used in equation (1). Larger values of this size index indicate a larger concentration of smaller aerosol particles, such as those which may have a continental source region. The variable phase function consists of a two-term Henyey Greenstein function used by Lenoble (1985) that includes a weighting factor and two asymmetry parameters.

Haggerty et al. (1990) provides background on SATVIS model input parameters, including maximum values for satellite zenith angle, AVHRR channel 2 radiance (to test for low clouds), and the difference between adjacent pixels in channel 2 (to test for partial cloudiness). Minimum values are specified for the solar reflection angle, channel 4 brightness temperature (as a high cloud test), and the ratio between channels 1 and 2 (to ensure clear pixels). All model runs in this report specified a satellite zenith angle less than 50° and a solar reflection angle greater than 35°. These thresholds ensured that the effects of ocean surface specular

reflection were minimized and that optical depth measurements were not attempted at extreme satellite viewing angles with an excessive radiative path length through the atmosphere. The calculation of aerosol optical depth and meteorological range is depicted in Figure 1. The details of the SATVIS model methodology are provided by Haggerty et al. (1990).

b. Navy Aerosol Model

The Navy Aerosol Model was developed by Gathman (1983) using the relationships between routinely-measured meteorological variables and aerosol concentration and size distribution in marine environments. The model provides information on aerosol properties and meteorological range over a wide range of open ocean regions where in-situ visibility observations are scarce. Additionally, since visibility observations typically rely upon a trained observer viewing known objects at known distances (a rare occurrence in open ocean areas), the Navy Aerosol Model may actually be more accurate than visibility observations. While the horizontal coverage of the Navy Aerosol Model typically is limited due to its dependence on in-situ measurements as input data, the coverage may be extended by using grid data from global or regional forecast models. NOGAPS data fields obtained from the Fleet Numerical Oceanography Center (FNOC) were used as Navy Aerosol Model for this study.

The model provides aerosol extinction coefficients and optical depth for visible and infrared wavelengths using

observations of wind speed, a 24-hour average wind speed, surface relative humidity, and the air mass type. Air mass type is specified by an air mass parameter which describes the estimated mix of continental and marine aerosols in the marine boundary layer. The output with the SATVIS meteorological range estimates.

Meteorological range predictions of the Navy Aerosol Model will reflect shortcomings in the NOGAPS fields used as input. Primarily, the spatial resolution of the NOGAPS grids is far less than that of the AVHRR data. Thus, small scale features in the aerosol patterns will not be detected. Additionally, any errors inherent in NOGAPS will affect the accuracy of the meteorological range estimates. For example, a dry bias in the NOGAPS moisture field would produce erroneously high meteorological ranges.

3. DATA

a. Satellite

The satellite data used as input for the SATVIS model consisted of NOAA9/11 AVHRR Local Area Coverage (LAC) data sets provided by the Atmospheric Directorate of the Naval Oceanographic and Atmospheric Research Laboratory (NOARL WEST). This LAC data was originally collected with the Persian Gulf region as the target area. For the area of interest in this report (northern Arabian Sea), 99 individual satellite passes were screened for applicability. Satellite data ingest, calibration, navigation, and screening were

accomplished on a NOARL WEST HP-835 computer using the TeraScan software package. Of the original 99 satellite passes, approximately 30 percent were too far west of the area of interest; thus, the maximum threshold for the satellite zenith angle (50°) was exceeded for the entire area and SATVIS model runs were not possible. Approximately 20 percent of the passes contained large areas that did not meet the minimum solar reflectance angle criterion (35°). Another 10 percent were considered too cloudy to provide meaningful results from the SATVIS model. The remaining passes were prioritized into case studies, with high priority given to passes on consecutive days with little cloudiness. These case studies are listed in Table 1.

An advantage to using the NOARL WEST HP-835 system is access to the Naval Environmental Operational Nowcasting System (NEONS) (Shaw et al., 1990; Jurkevics et al., 1990) and the Navy Aerosol Model. This allowed satellite data processing, NOGAPS data retrieval and analysis, execution of image display options, and SATVIS/Navy Aerosol Model inter-comparisons to be accomplished on a single system. For the purposes of comparing the models, SATVIS output was subsampled to an ASCII file and converted to surface aerosol extinction. Assuming a boundary layer depth of 1 km, the surface aerosol extinction was converted to meteorological range and compared with estimates from the Navy Aerosol Model.

TABLE 1. Local Area Coverage (LAC) Data used for SATVIS Analyses

YEAR	MONTH DAY	PLATFORM	ORBIT START TIME (UT)
88	OCT07	NOAA-9	11:12600
88	OCT25	NOAA-9	11:15988
88	OCT26	NOAA-9	11:13960
88	OCT27	NOAA-9	11:29962
88	NOV02	NOAA-9	11:30006
88	NOV03	NOAA-9	11:28060
88	DEC05	NOAA-11	09:13015
88	DEC06	NOAA-11	09:02020
88	DEC07	NOAA-11	08:53008
88	DEC08	NOAA-11	08:43066
88	DEC14	NOAA-11	09:21102
88	DEC15	NOAA-11	09:11166
88	DEC16	NOAA-11	09:01180
89	JAN23	NOAA-11	09:25706
89	JAN24	NOAA-11	09:15700
89	JAN25	NOAA-11	09:05738
89	JAN26	NOAA-11	08:55708
89	MAY01	NOAA-11	09:35088
89	MAY02	NOAA-11	09:25102
89	MAY03	NOAA-11	09:15106

b. Model Fields are In-Situ Observations

Archived NOGAPS data fields were acquired through NEONS and utilized as input to the Navy Aerosol Model. Additionally, surface/radiosonde observations, surface optimal interpolation (OI) analyses, and constant pressure OI analyses for 850 and 700 mb were obtained from the NOGAPS data archives via the NOARL WEST Meteorology Laboratory. These products were used to assess the synoptic conditions.

Fields of temperature, pressure, vapor pressure, and wind components were obtained from NOGAPS 3.0 archives. These surface level fields were derived by interpolation in a data sparse region and thus may not exactly reflect actual meteorological conditions. Accordingly, these data fields may partially contribute to errors in Navy Aerosol Model output. Additionally, these data fields do not have the resolution necessary to identify small mesoscale variations in optical depth due to sharp humidity gradients.

Air mass parameter values for input to the Navy Aerosol Model were estimated based on the presence of continental sources of aerosol surrounding the area of interest. Since the region of interest is in close proximity to multiple continental aerosol sources, higher values of the air mass parameter seem appropriate. A value of 5 was used for onshore flow cases, 7 for offshore flow, and 6 for intermediate cases.

All the cases we investigated are discussed, but we only present figures for two series of dates: 25-27 October 1988

and 14-16 December 1988. Both series of dates have several traits in common. First, in both the optical depth images show relatively high values in coastal regions. As reported by Haggerty et al. (1990), excessive oceanic turbidity can produce reflected values of the same order of magnitude as those from aerosol particles. Additionally, subsurface reflection from shallow bottom regions is an additional source of error. Both high turbidity and subsurface reflection occur in the coastal regions and estuaries within the area of interest in this study; therefore, optical depth, Ch1/Ch2 ratio and SATVIS meteorological range calculations should be ignored in these regions. Another factor common to all case studies is the cloud masking algorithm. The cloud-contaminated regions appear as dark areas on the images. Since the SATVIS model requires clear conditions, calculations are not possible if cloud contamination is present. The scaling varies from case to case, allowing maximum contrast of the often subtle variation in optical depth and the Ch1/Ch2 ratio. On the displays of the model intercomparison the ranges from each model are classified into three ranges (less than 10 km, 10-30 km, and greater than 30 km) as recommended by Haggerty et al.

4. RESULTS

a. Case Study, 07 October 1988

The first case study is representative of the transition season between the southwest and the northeast monsoon in the

northern Arabian Sea. This single pass (not shown) was selected not only on the basis of its relative absence of clouds, but also due to the synoptic wind pattern. The surface wind is southwesterly over most of the region, with cyclonic flow in the region of the Pakistan-India border as a result of the well-defined migratory low pressure center aloft over eastern Pakistan. A trough extends to the southwest over the central Arabian Sea (not shown). Coastal reporting stations do not report any significant restrictions to the surface visibility. Representative soundings show relatively stable and dry conditions aloft with no evidence of a strong inversion. A comparison between meteorological ranges calculated from SATVIS and from the Navy Aerosol Model show general agreement in the central Arabian Sea (not shown). As expected, SATVIS range values are lower than Navy Aerosol Model values in several areas, particularly in the eastern and western regions of coincident data.

b. Case Study, 25-27 October 1988

This second case study represented the first encounter with significant offshore flow, and the only case with a clear example of dust being advected from the continent out over the ocean surface. The 12 UT 25 Oct 88 surface, 850 mb and 700 mb NOGAPS OI analyses, and the Masroor AFB upper air sounding, are shown in Figures 2 through 5, respectively. These figures indicate general offshore flow in the lower levels of the atmosphere, as well as generally dry, stable conditions. The

offshore flow over the western Pakistani coast is significantly greater above the surface layer. Figures 6 and 7 display conditions 12-hours later. The development of a trough over the region, manifested in the low pressure center evident at 850 mb, has intensified the magnitude of the offshore wind flow in the atmosphere above the surface layer. This pattern is favorable for dust from inland highlands to be picked up and advected over the ocean surface. The fact that surface winds do not seem to support this dust advection suggests that any dust advected offshore would be suspended aloft during the early stages of the event. A dust plume over the western coast of Pakistan is clearly evident in the enhanced Channel 1 imagery (not shown). Over the period of this case study, the dust appears to be advected to the south and to the southwest, consistent with the wind field above the surface layer. Clouds associated with the troughing are also present over the east-central Arabian Sea.

The SATV1S images of optical depth and Ch1 /Ch2 ratios are shown in Figures 8 and 9, respectively. The optical depth images show lower values (near 0.15) in the clear regions near equatorial waters. Optical depths above 0.4 are coincident with the young dust plume on the 25 Oct image. Even more significant are the high optical depth values offshore on the following day. The images of Ch1/Ch2 in Figure 9 illustrate the problems encountered when using the SATVIS model in regions of high continental aerosol concentration. Although

high Ch1 /Ch2 values should indicate areas of continental aerosol influence, within the dust plume the ratios are actually lower. These lower ratios are probably the result of two factors - (1) greater albedo in Channel 2 resulting from the concentration of dust, and (2) the more complex scattering and absorbing characteristics of continental aerosols, especially in such a high range concentration. The assumption of well-behaved, spherical aerosols with a single scattering albedo of unity is no longer valid. As a result, the scattering phase function derived from Ch1/Ch2 in support of the optical depth calculation would be in error in this region; accordingly quantitative estimates of the optical depth are also likely to be in error. Another problem observed in Figure 9 is the sunglint contamination in the eastern portions of the images for Oct 25 and 26. Although SATVIS screens the data for specular reflection using a combination of the solar reflection angle and satellite zenith angle, variations in the absorptive/reflective properties of the ocean surface as a result of solar zenith angle appear to create abnormally high Channel 1 values when the solar and satellite zenith angles are both large but in opposite directions of azimuth.

The comparison between SATVIS and Navy Aerosol Model meteorological ranges are shown in Figures 10 through 12. As in the first case study, the range estimates are in general agreement, with the SATVIS estimates being more pessimistic

than those from the Navy Aerosol Model. Low range values resulting from the dust event are evident in the SATVIS ranges for Oct 25 and 26. In this case, SATVIS may not be accurately representing surface meteorological range (i.e., visibility) if the dust is suspended above the surface layer as is suggested by the available synoptic data. The model assumes that all scatterers are confined to the MABL, even though contributions to the upwelling may originate at any level in the atmosphere. As a result, the SATVIS model may substantially underestimate the boundary layer meteorological range in regions where high concentrations of aerosols (of either continental or marine origin) exist above the boundary layer.

c. Case Study, 02-03 November 1988

This case study was selected to examine the meteorological ranges estimated by SATVIS in conditions of high solar and satellite zenith angles of opposite azimuths. Both satellite passes were near the maximum satellite zenith angle (50°) and solar reflection angle (40°) identified as SATVIS model criteria for ensuring meaningful results from the data. Synoptic conditions reflect light, northerly offshore flow over the region at each of the three levels. Satellite imagery (not shown) indicates that the Arabian Sea is generally cloud free with the exception of the extreme southeastern portion of the study area. The SATVIS imagery of optical depth and CH1/Ch2 (not shown) show the effects of

solar specular reflection throughout the region. Although the optical depth and Ch1/Ch2 values seem to be contaminated by specular reflection, the small range in Ch1/Ch2 (1.7 - 2.0) allows reasonable estimates of optical depth (and thus, meteorological range) to be generated. A comparison of the two models (not shown) reveals the same general agreement that was observed in the previous two case studies.

d. Case Study, 05-08 December 1988

The northeast monsoon circulation had become well established in the Arabian Sea by early December 1988. Climatology for this area indicates that wintertime conditions are relatively placid, with light winds, calm seas, and generally clear conditions. With regard to marine aerosols in the MAIL, production mechanisms are at a minimum and one would anticipate low extinction in visible wavelengths and greater meteorological ranges than during other seasons.

Synoptic data representing the period of this case study confirms the monsoon flow. Wind velocities are relatively light in each layer, and the surface wind flow remains basically from the north to northwest throughout the period. A stronger north-south temperature gradient exists over northern coastal areas due to the contrast between the mild subtropics and the colder mid-latitude conditions that exist over the continent to the north as a result of the season.

Satellite imagery (not shown) indicates a large region of cirrus clouds bisects the study area on the first day. This

area of high clouds is advected to the west, although the remaining days still contain scattered high clouds and a cloud cluster associated with a small tropical circulation that appears on the third day. The northern third of the Arabian Sea remains relatively free of low clouds. SATVIS-derived optical depth and Ch1/Ch2 images (not shown) reveal an area of higher optical depth and Ch1/Ch2 on 07 and 08 Dec in the clear ocean areas to the north of the tropical cloud formation. This area appears to be under the influence of a concentration of continental aerosols due to the higher Ch1/Ch2 values, but the reflectance values in Channel 1 in this region are among the lowest in the case study. In fact, the higher Ch1/Ch2 values appear to be a result of a decrease in Channel 2 reflectance rather than an increase in Channel 1 that would be expected in conjunction with an increase in the concentration of continental aerosols. This feature is advected with the wind flow, supporting the hypothesis that it is an atmospheric phenomenon and not the result of a sea surface event such as a plankton bloom. It is possible that some particular constituent in the atmosphere in this region has unique wavelength-dependent scattering/absorbing characteristics that create the effect observed in this case study, but there are no data to support this claim other than the satellite imagery.

Comparisons between meteorological ranges from SATVIS and the Navy Aerosol Model show that meteorological ranges from

both models are significantly greater than previous case studies, as expected with the light northeast monsoon winds. The models are in good general agreement, although a few small areas have satellite-derived ranges that are greater than those from the Navy Aerosol Model (unlike previous cases). One explanation may be the subsidence over the region associated with the northeast monsoon flow. This subsidence may tend to confine aerosols to the boundary layer and reduce the possibility of aerosol contribution to the upwelling radiance above the boundary layer. Thus, SATVIS would be less likely to underestimate meteorological ranges since its assumption that all extinction occurs in the MAIL would be more reliable. The SATVIS output also shows scattered regions of reduced meteorological range, probably resulting from atmospheric moisture variations in the vicinity of clouds that require resolution greater than that available from the Navy Aerosol Model.

e. Case Study, 14-16 December 1988

Figures 13 through 15 show the wind and temperature patterns throughout the three day period represented by this case study. The wind patterns correspond well to that expected in the Arabian Sea northeast monsoon circulation in mid-December. The associated AVHRR satellite imagery (not shown) reveals several clear regions separated by areas of cellular tropical cumulus. SATVIS optical depth and Ch1/Ch2 images are shown in Figures 16 and 17 and reveal widespread

areas of possible continental aerosol influence particularly near the Gulf of Oman and the coast of India. Relatively low optical depth values of 0.14 are evident. These areas of possible continental influence correlate well with offshore surface winds depicted in Figure 13. Due to the unavailability of NOGAPS data fields on 14 and 15 December, a model comparison was only possible for the last day. This comparison is shown in Figure 18. As was observed earlier in the month, estimated range values are consistent between the models and are relatively large. Again, the SATVIS data show greater detail and lower meteorological ranges in the vicinity of clouds.

f. Case Study, 23-26 January 1989

This mid-winter case study was characterized by the least amount of cloud contamination of any of the case studies selected for this report. With the exception of 25 January, the Arabian Sea was generally cloud free north of 22°N. Synoptic charts show that the northeast monsoon continues to dominate the region. The surface winds back to the northwest near the end of the case study, under the influence of ridging behind the low center over eastern Pakistan. The polar frontal zone has moved south to a seasonal extreme near 300N. Although this zone is not apparent in the 850 or the 700 mb analyses (not shown) at 12 UT on 23 Jan, evidence of this baroclinic zone can be found at higher levels in the form of westerly wind maxima.

The satellite imagery (not shown) confirm the presence of a clear ocean surface to the north on the first two days. These data also reveal cumulus development over the region on Jan 25, and the formation of a convergence zone between the northerly monsoon flow and the tropics on the final case study day. The SATVIS images of optical depth and Ch1/Ch2 (not shown) display expected low values of optical depth (generally 0.11) and Ch1 /Ch2 (generally 3.0) with the notable exception of the images for 24 Jan. On this day, a unique pattern of optical depth and Ch1 /Ch2 appears near 19°N, 63°E which defies any previous description. There are both low and high values of each variable in this region, and the model appears to have masked some of the pixels in the vicinity. However, pixels that appear to be masked in one image are classified in the other, suggesting that the cloud classification criteria in the model is not responsible for the lost pixels. Several combinations of values used as input to the pixel classification scheme were attempted during processing (e.g., maximum Channel 2 radiance, minimum Ch1/Ch2, minimum Channel 4 brightness temperature, and maximum acceptable difference in Channel 2 radiance between adjacent pixels) in an effort to identify the sensitivity in the SATVIS model, all with little success. It is not clear whether this pattern portrays an actual physical phenomenon in the atmosphere or a limitation in the SATVIS processing algorithm.

As with the other wintertime cases, the SATVIS and the

Navy Aerosol Model correspond quite well (not shown). Both give the extended ranges anticipated from climatology and the available synoptic data. It is interesting to note that the unique optical depth feature observed on 24 Jan has little effect on the meteorological ranges subsampled from the SATVIS data, with the exception of a small area of slightly lower range values and some missing data.

g. Case Study, 01-03 May 1989

The final case study is coincident with a transition from the northeast to the southwest monsoon. Unlike wintertime conditions, the onset of the southwest monsoon is characterized by the commencement of southwesterly winds at the surface and increasing cloudiness due to the advection of moisture and heat from the tropics. From the perspective of this report, less aerosols of continental origin should be observed. If aerosols above the boundary layer are transported upward through some sort of convective mechanism, then the low range estimates made by the SATVIS model may become more prevalent as the southwest monsoon strengthens. Southwesterly winds exist in the central and southern portions of the study area, although winds at 850 and 700 mb continue to persist out of the northwest. The AVHRR images (not shown) indicate large areas of strong convection forming over the region to the southeast. The northwestern portions of the Arabian Sea remain relatively cloud free through the period. The images of SATVIS optical depth in (not shown) indicate

optical depth values in this region less than 0.13, with the exception of an area near the Iranian coast on 01 May and a broad band in the center of the study area on 02 May with optical depths reaching 0.16. Although these values appear high in the image, they are considerably smaller than those observed in previous case studies under the influence of continental aerosols (e.g., optical depths as high as 0.45 were observed in the 25-27 Oct 88 case study). An analysis of Ch1/Ch2 for this case (not shown) supports the conclusion that the slightly higher optical depths observed on 01 and 02 May are due to a marine phenomenon, perhaps aerosol growth due to higher relative humidities over the ocean surface. Ch1/Ch2 values do not exceed 3.0 at any location in the clear area to the north. SATVIS and Navy Aerosol Model meteorological ranges (not shown) are consistent for these three days. The plots for 01 and 02 May illustrate the ability of SATVIS to detect restrictions to visibility that are too detailed to be observed by the Navy Aerosol Model. The apparent lack of contamination by continental dust allows a high degree of confidence in the SATVIS-generated meteorological ranges.

5. CONCLUSIONS

A subset of 20 NOAA-9/11 AVHRR satellite subscenes in seven case studies were screened from 99 original daytime passes and were utilized as the data source for the SATVIS meteorological range estimation model. Variations in satellite-derived optical depth and Ch1/Ch2 were observed in

these data. Comparisons with the Navy Aerosol Model (based on NOGAPS data field input) were accomplished for 18 of these 20 subscenes.

Based on the broad range categories originally used by Haggerty et al. (1990) (0-10 km, 10-30 km, and greater than 30 km), meteorological ranges derived with the SATVIS model generally agreed with those obtained utilizing the Navy Aerosol Model. Due to uncertainties in the accuracy of the NOGAPS data fields and the lack of in-situ data, more detailed range resolution was not possible. The SATVIS model was able to identify mesoscale impacts on meteorological range that could not be resolved by the Navy Aerosol Model using the available data. In several cases the SATVIS model appeared to underestimate meteorological ranges as compared to those provided by the Navy Aerosol Model and the extremely limited in-situ data. This tendency was minimized in the area of study during the northeast monsoon, when conditions in the lower atmosphere were relatively dry and stable due to the seasonal subsidence. This effect supports the conclusion that SATVIS output may be affected by aerosols residing above the boundary layer that do not have an impact on surface visibility.

A limitation of SATVIS is the availability of useful data. Approximately 40 percent of the satellite data could not be used with the model due to large satellite zenith angles, small solar reflection angles, or extensive

cloudiness. This percentage would certainly be less in regions of persistent cloud cover (e.g., the Intertropical Convergence Zone, the summertime eastern Pacific/Atlantic, etc.). At high latitudes, the extent of polar orbiting satellite coverage would tend to offset this disadvantage.

Images of SATVIS optical depth and Ch1/Ch2 provided an excellent qualitative estimate of the impact of dust advected offshore. The Ch1/Ch2 image for 25 Oct 88, in particular, illustrates the extent of the dust plume clearly. However, due to the complications added to the radiative transfer approximation (i.e., the different size, shape, concentration, and absorptive/ reflective properties of the dust particles), the SATVIS model cannot make quantitative measurements in these regions. Optical depth estimates within the dust plume were probably underestimated.

A few SATVIS-generated optical depth and Ch1/Ch2 images (e.g., 07 Dec 88, 24 Jan 89) revealed geographic areas where the pixel classification could not be explained. It is unclear whether these effects were due to an actual physical phenomenon in the atmosphere or to limitations in the SATVIS model.

Although the SATVIS model masks pixels with a small solar reflection angle, contamination due to surface specular reflection was observed at reflection angles as high as 50°. Contributing factors may be the strong dependence of ocean surface specular reflection on solar zenith angle and on sea

state. In cases where the range of Ch1/Ch2 values were small, the SATVIS model still produced reasonable meteorological range estimates even though some discontinuities were observed in the optical depth and Ch1/Ch2 images.

A goal of this study was to assess the applicability of SATVIS as a Navy Tactical Decision Aid (TDA) for incorporation into Navy meteorological data processing equipment such as the Tactical Environmental Support System (TESS). While the model shows promise in the provision of over-the-horizon visibility data to tactical users, the following items would need to be addressed and/or incorporated into SATVIS before its use as a TDA would be widely accepted by Navy operational users:

a. The ability to provide horizontal slant-range visibility from (and to) a specified altitude rather than a simple estimate of horizontal visibility near the surface. This capability would require knowledge of the vertical variation of aerosol concentration within the boundary layer and in the lower troposphere;

b. greater range resolution (to the nearest km) for surface and slant-range visibility less than 10 km;

c. the ability to blend with other meteorological range estimation models and in-situ data in order to compensate for limitations in satellite coverage.

6. RECOMMENDATIONS

The Naval Oceanic Vertical Aerosol Model (NOVAM) (de Leeuw et al., 1989; Gathman et al., 1989) should be examined

as a possible solution to the problems of: (1) identification of the vertical distribution of aerosols within the boundary layer; and (2) extracting meteorological range estimates for regions with little or no satellite coverage. NOVAM is an ideal candidate for a blend of models and in-situ data as recommended by Haggerty et al. (1990).

SATVIS must have the ability to estimate the radiance contribution due to the presence of aerosols above the boundary layer. The distribution and composition of aerosols at these levels is not well understood. Data from a global aerosol climatology such as that recommended by Stowe et al. (1989) could provide SATVIS the ability to parameterize the error in meteorological range estimates due to aerosols above the boundary layer. Some knowledge of the residence times and physical/chemical properties of these aerosols as a function of their global distribution would improve such a parameterization.

Further validation of the SATVIS algorithms is required. The availability of in-situ ground truth meteorological range data should be a priority. With the increasing interest in global climatology, in-situ meteorological range data should become more available for use not only for validation of the model but also as a baseline value in a TDA.

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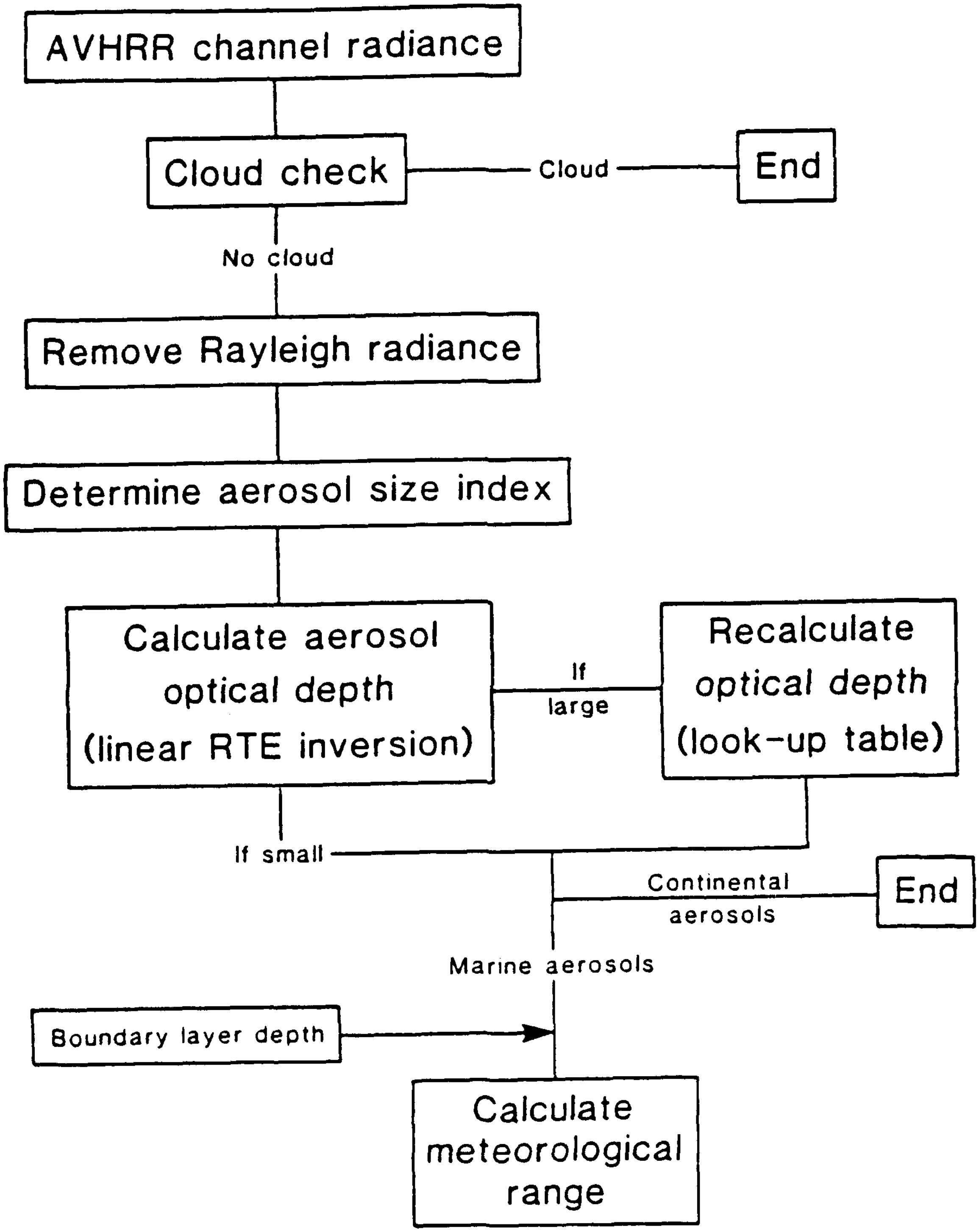

Figure 1: Schematic diagram showing the major features of SATVIS and the execution sequence (from Haggerty et al., 1990).

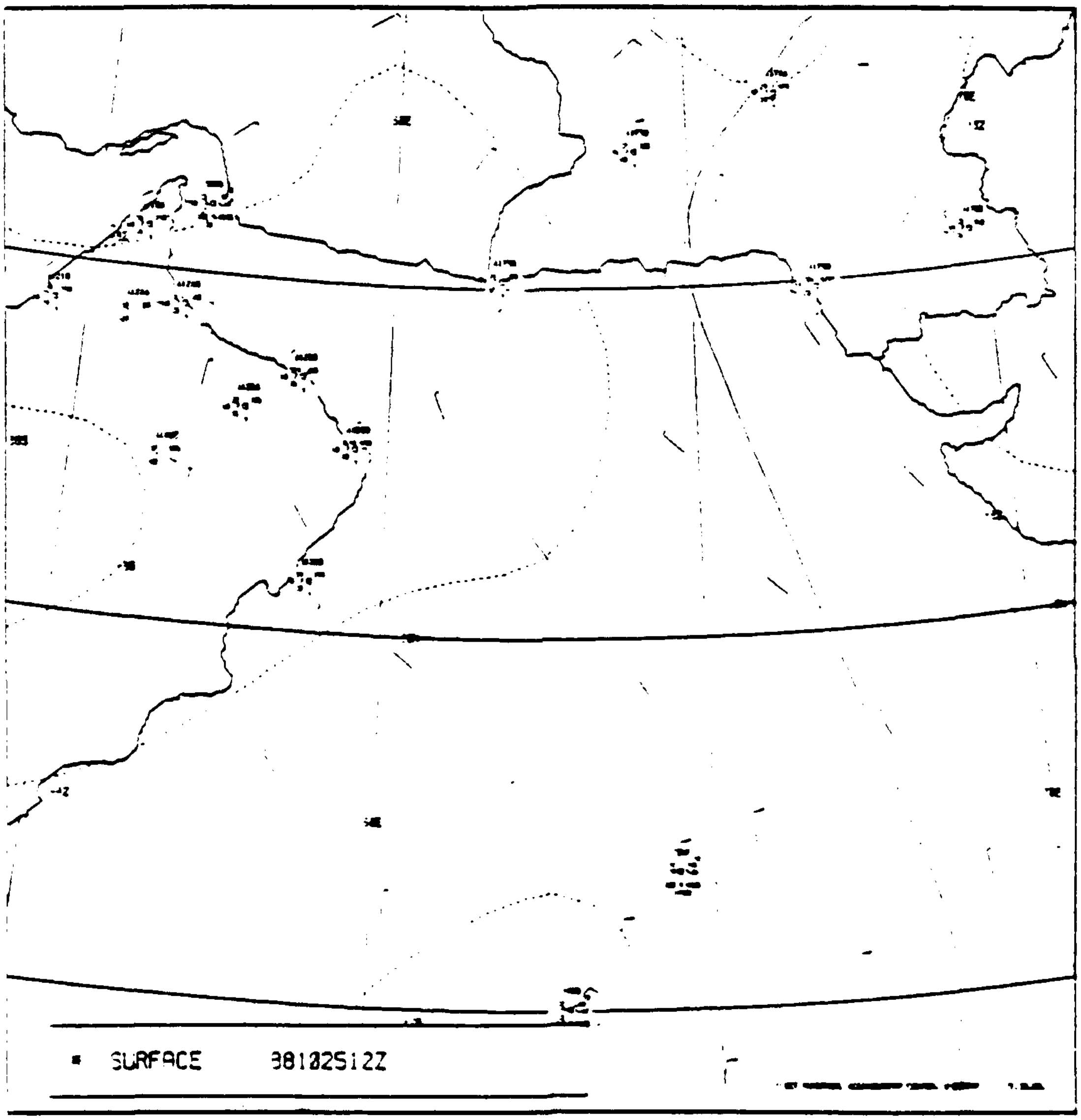

Figure 2: 12 UT 25 Oct 88 NOGAPS Surface OI Analysis.

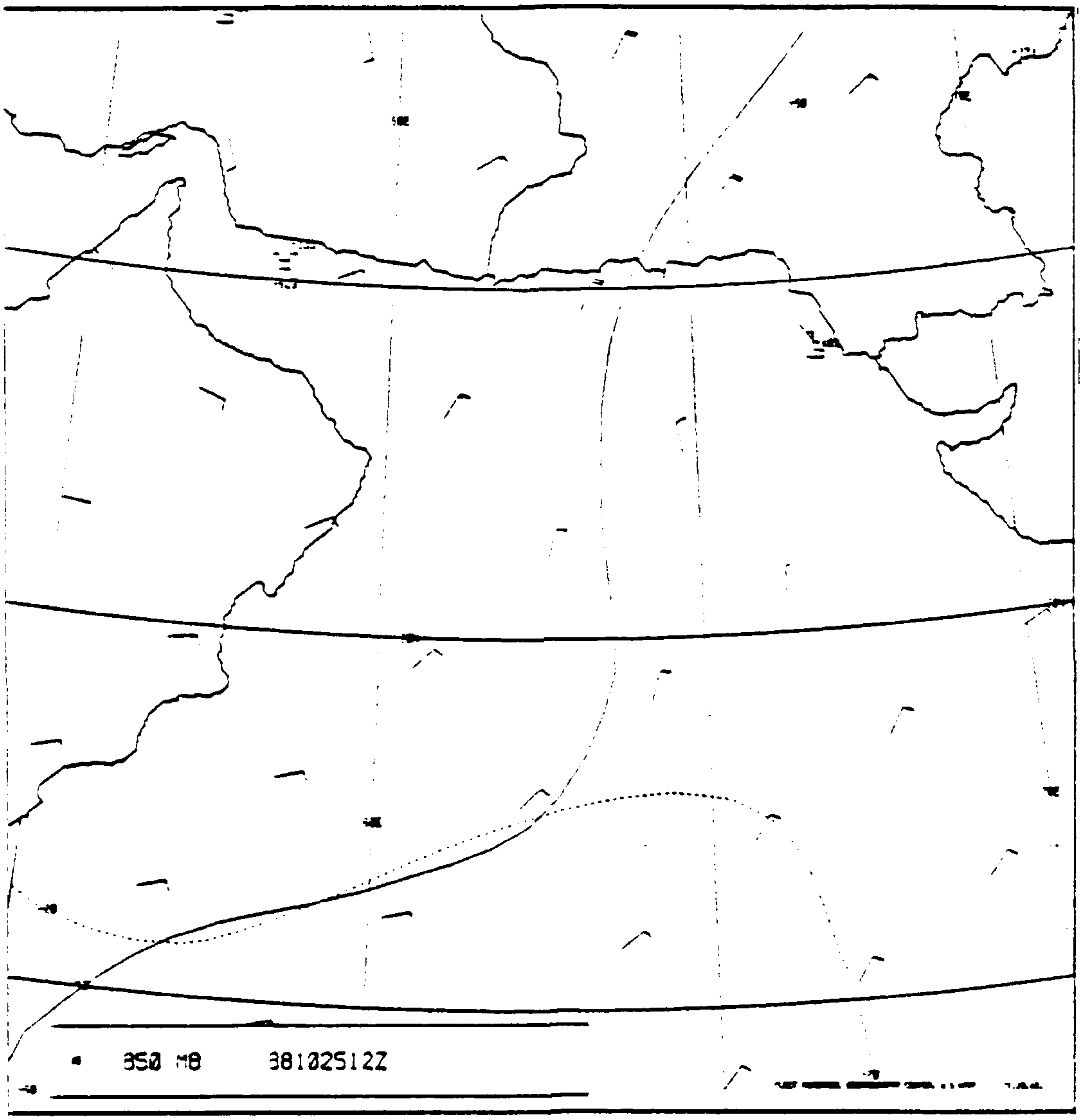

Figure 3: 12 UT 25 Oct 88 NOGAPS 850 mb OI Analysis.

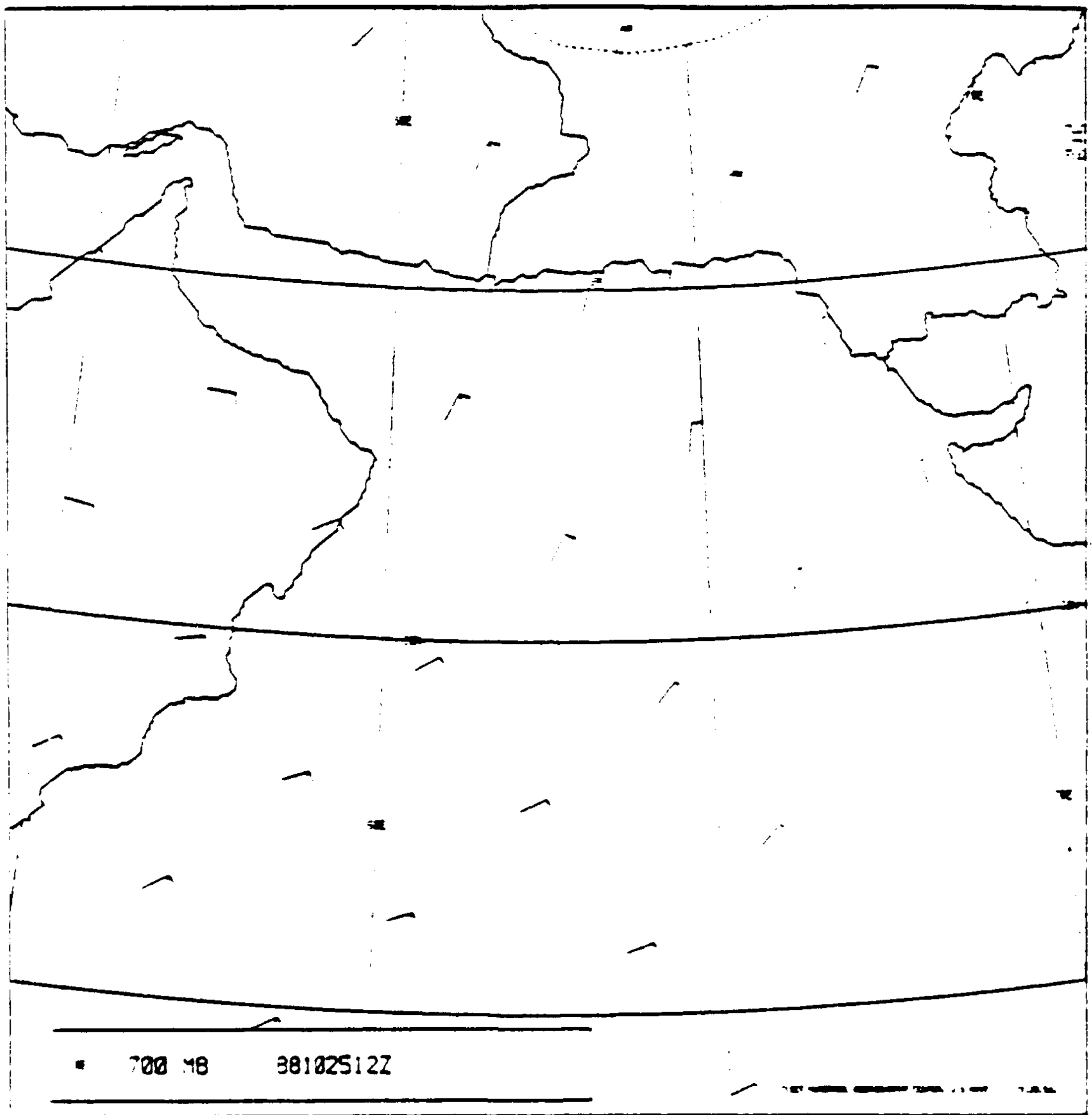

Figure 4: 12 UT 25 Oct 88 NOGAPS 700 mb OI Analysis.

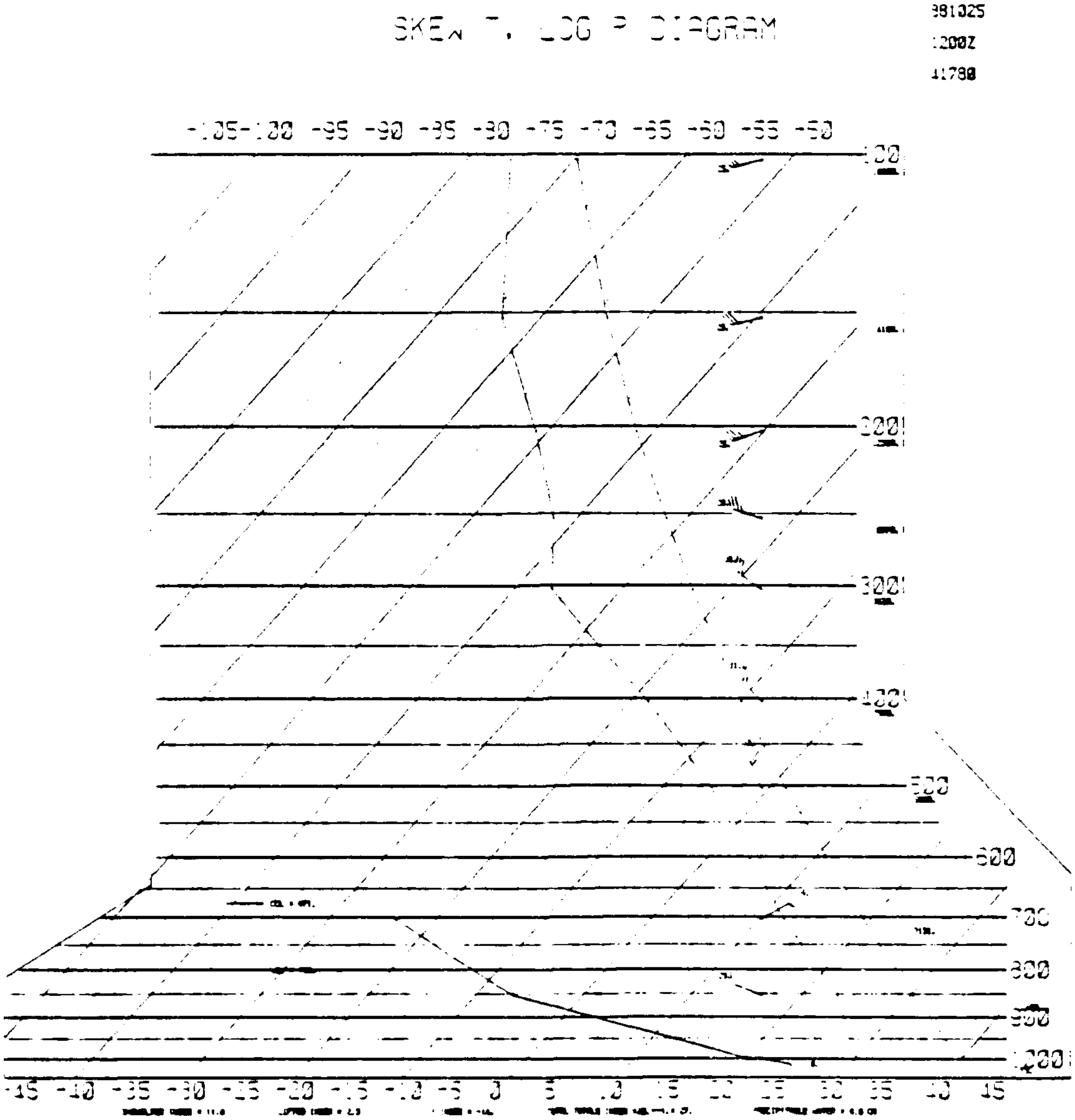

Figure 5: 12 UT 25 Oct 88 Skew-T Log-P Diagram for Masroor AFB, Karachi, Pakistan.

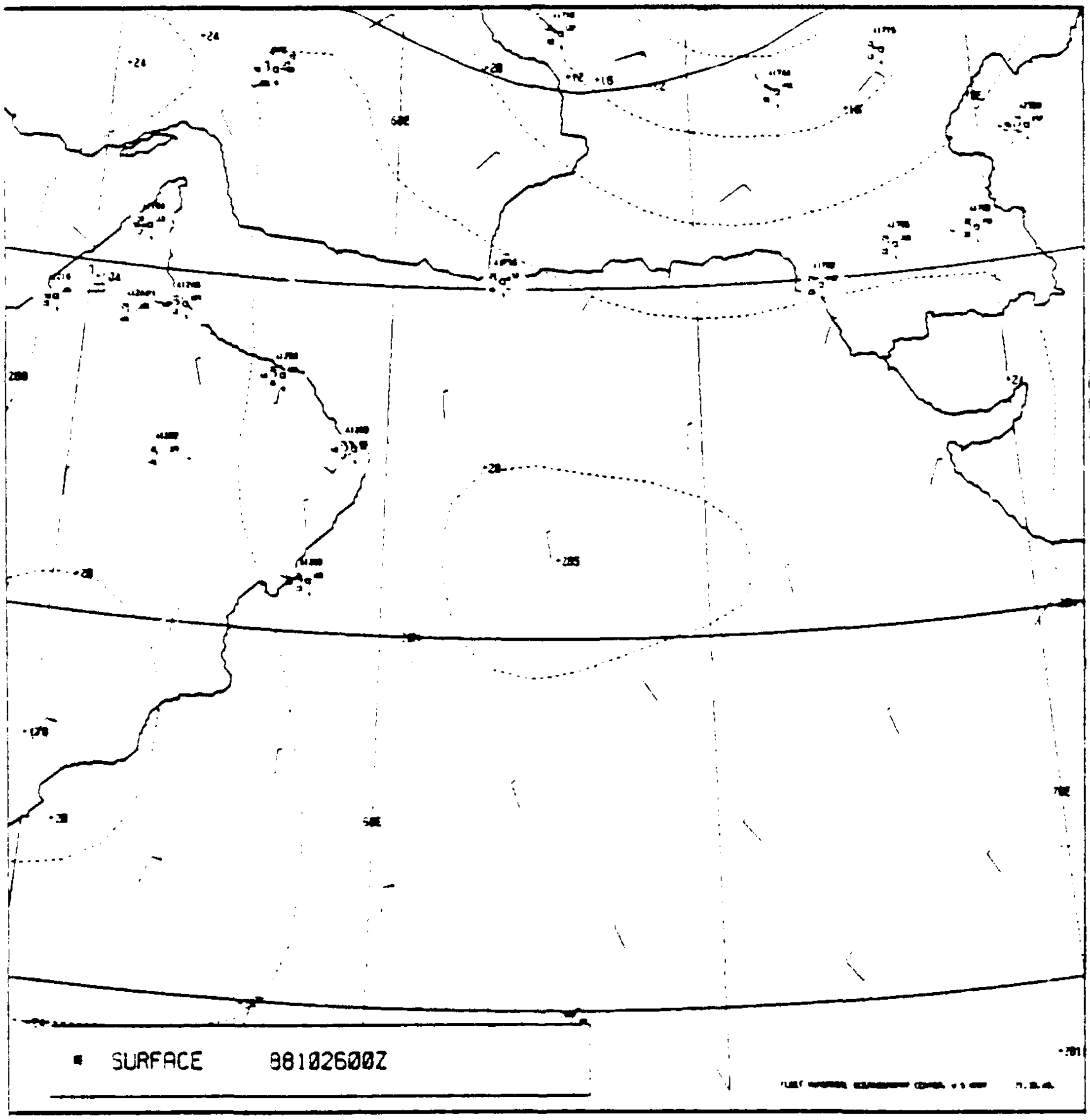

Figure 6: 00 UT 26 Oct 88 NOGAPS Surface OI Analysis.

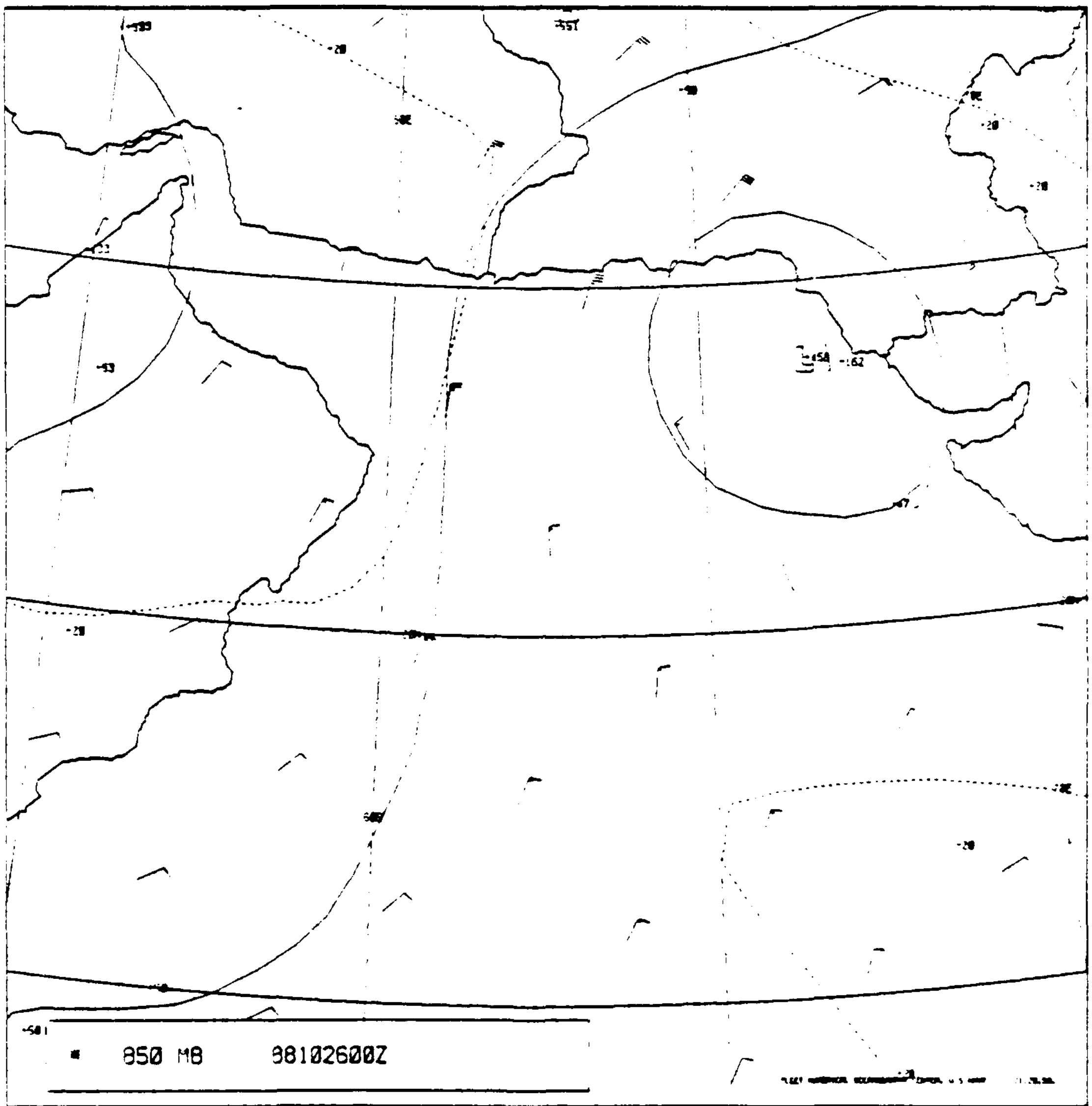

Figure 7: 00 UT 26 Oct 88 850 mb OI Analysis.

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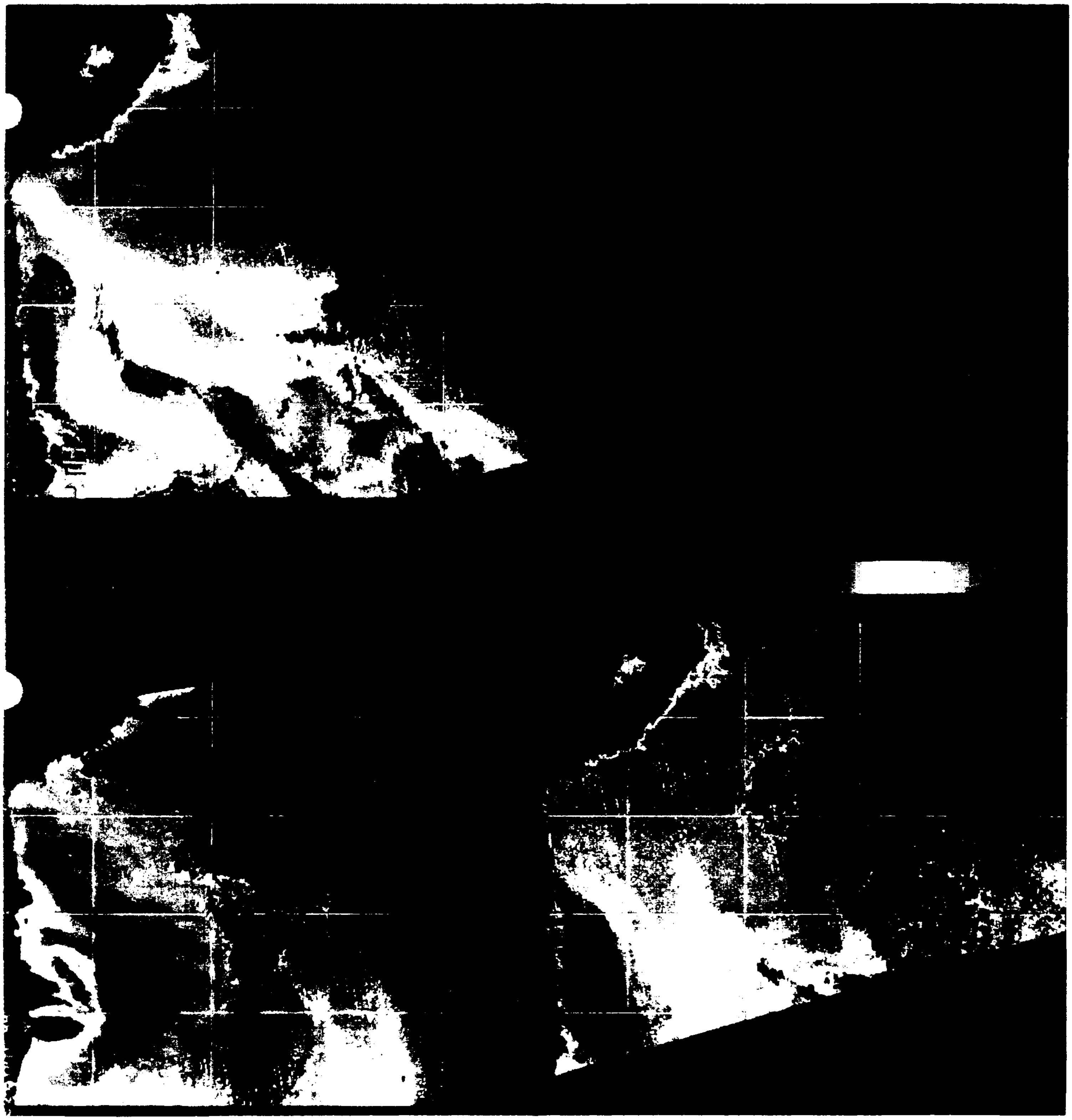

Figure 8: 25-27 Oct 88 SATVIS Optical Depth.

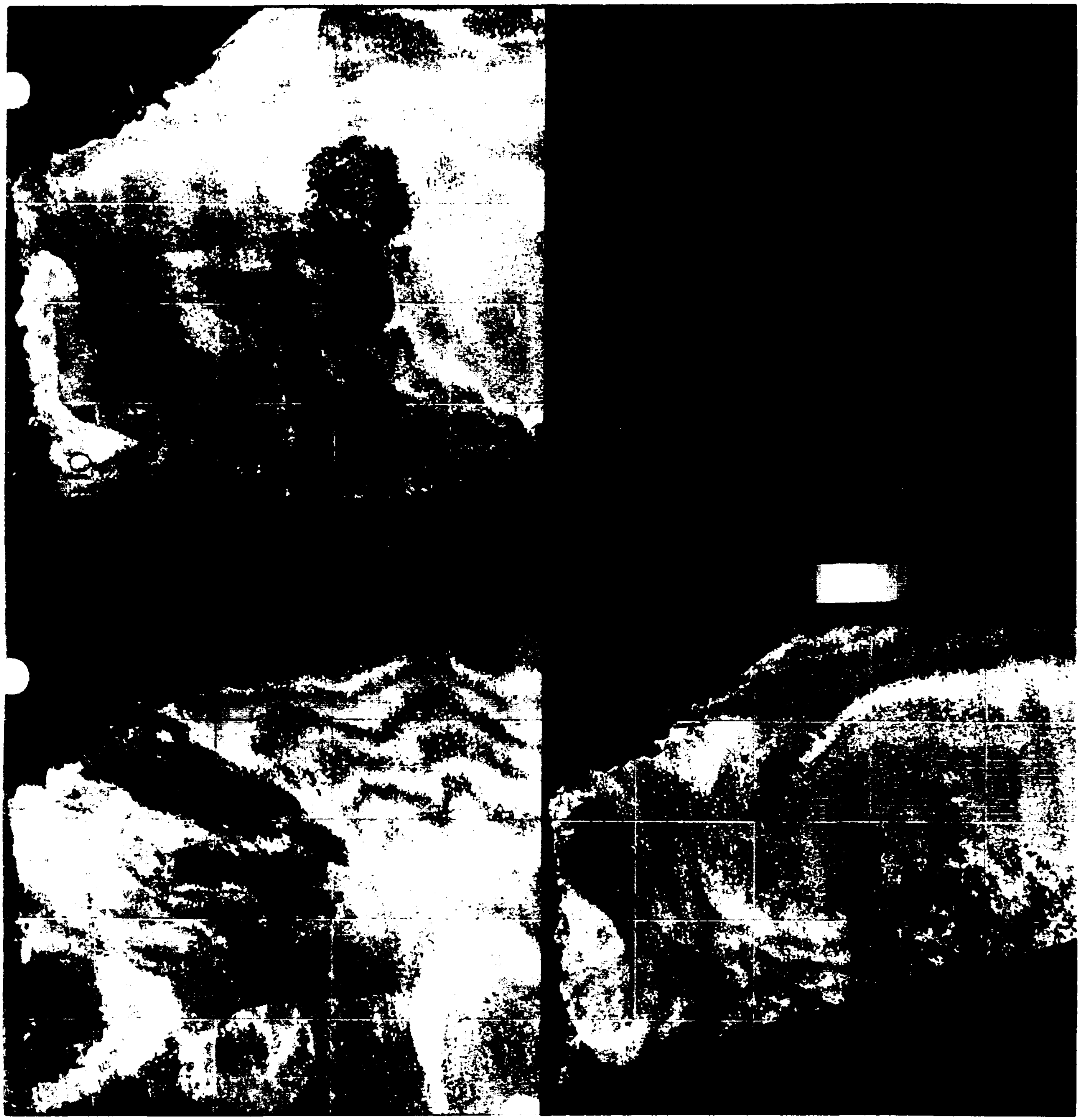

Figure 9: 25-27 Oct 88 SATVIS Ch1/Ch2 Ratio.

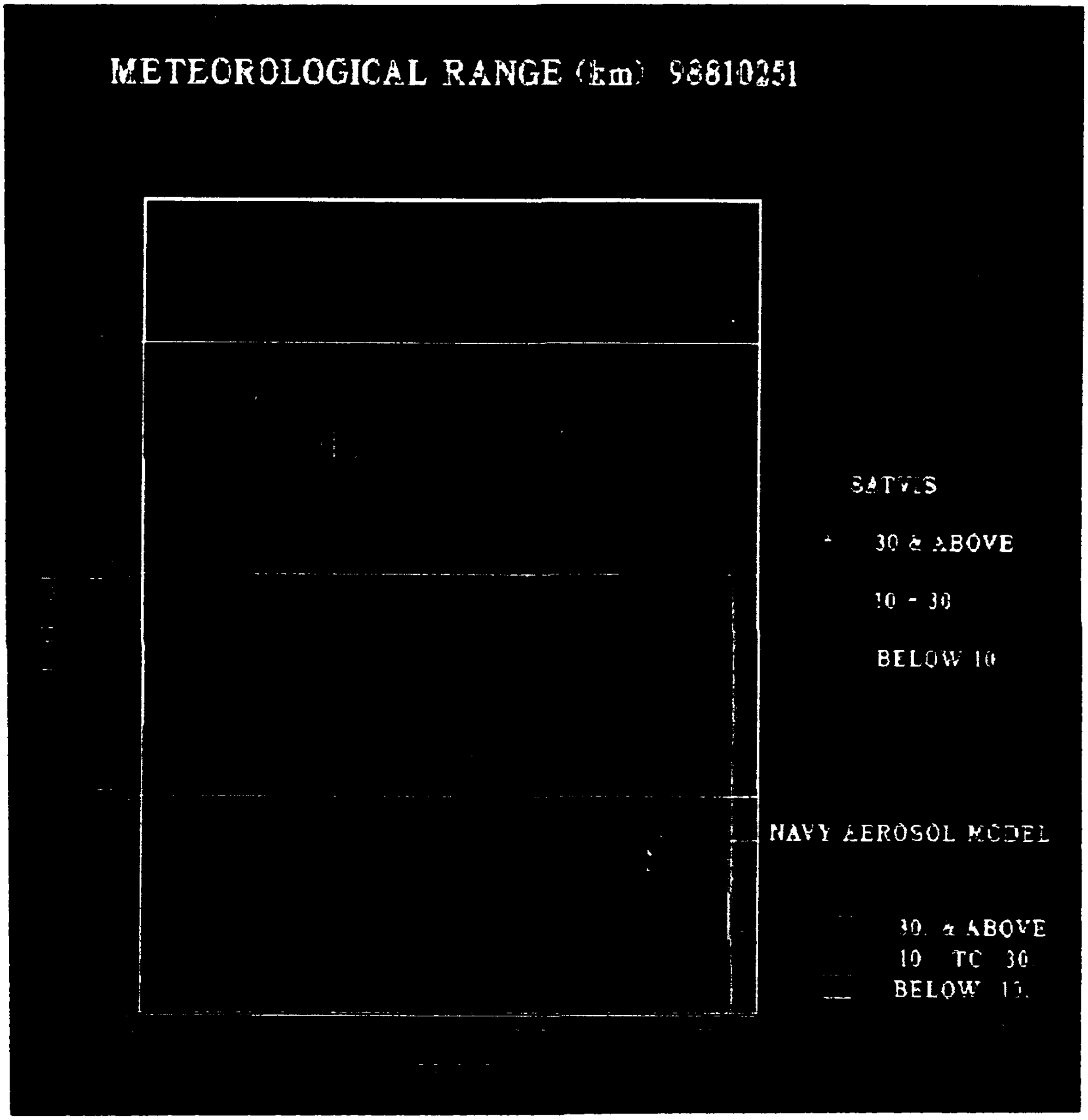

Figure 10: SATVIS and Navy Aerosol Model Ranges for 25 Oct 88. Ignore low values on extreme right of diagram.

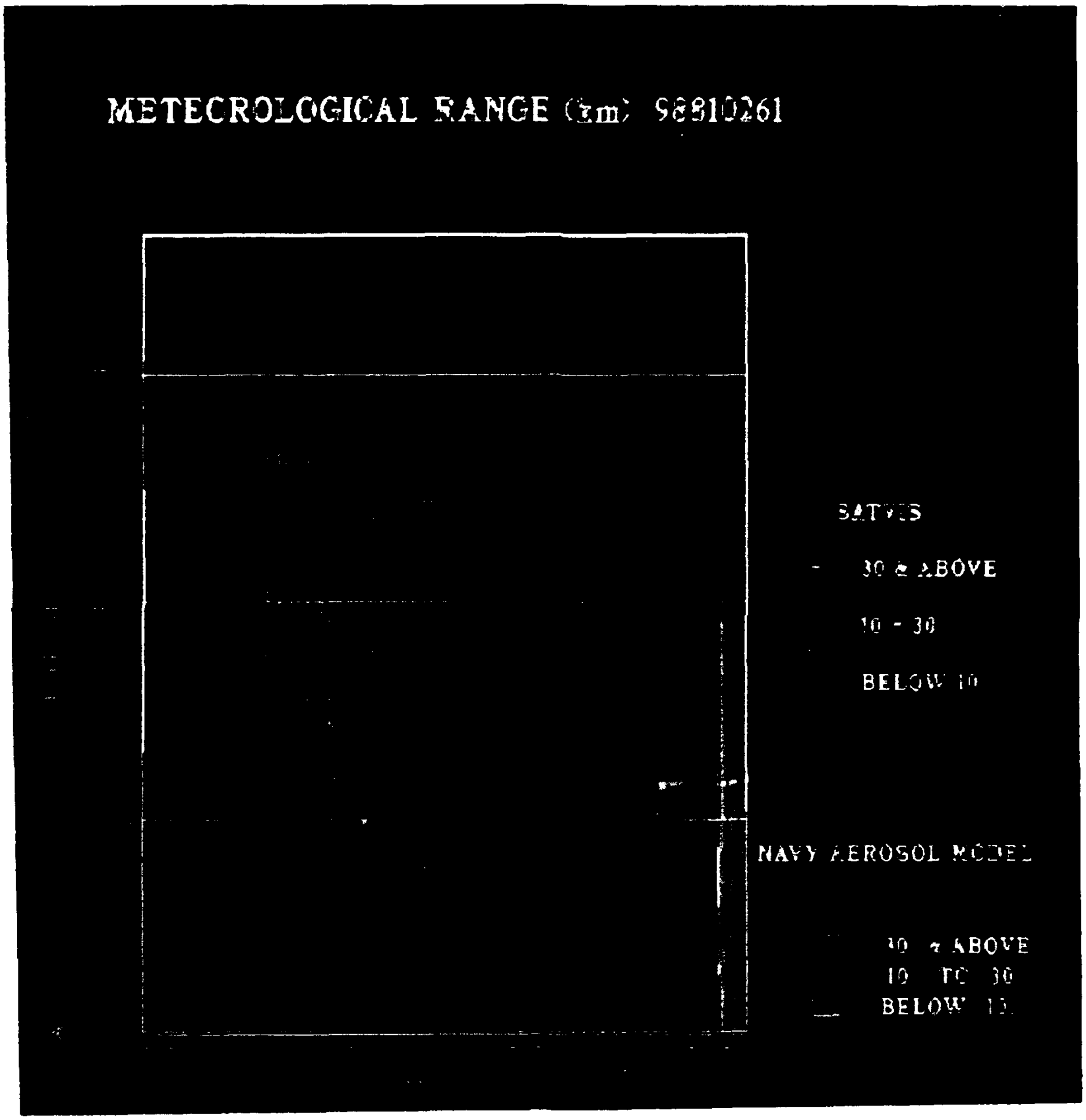

Figure 11: SATVIS and Navy Aerosol Model Ranges for 26 Oct 88. Ignore low values on extreme right of diagram.

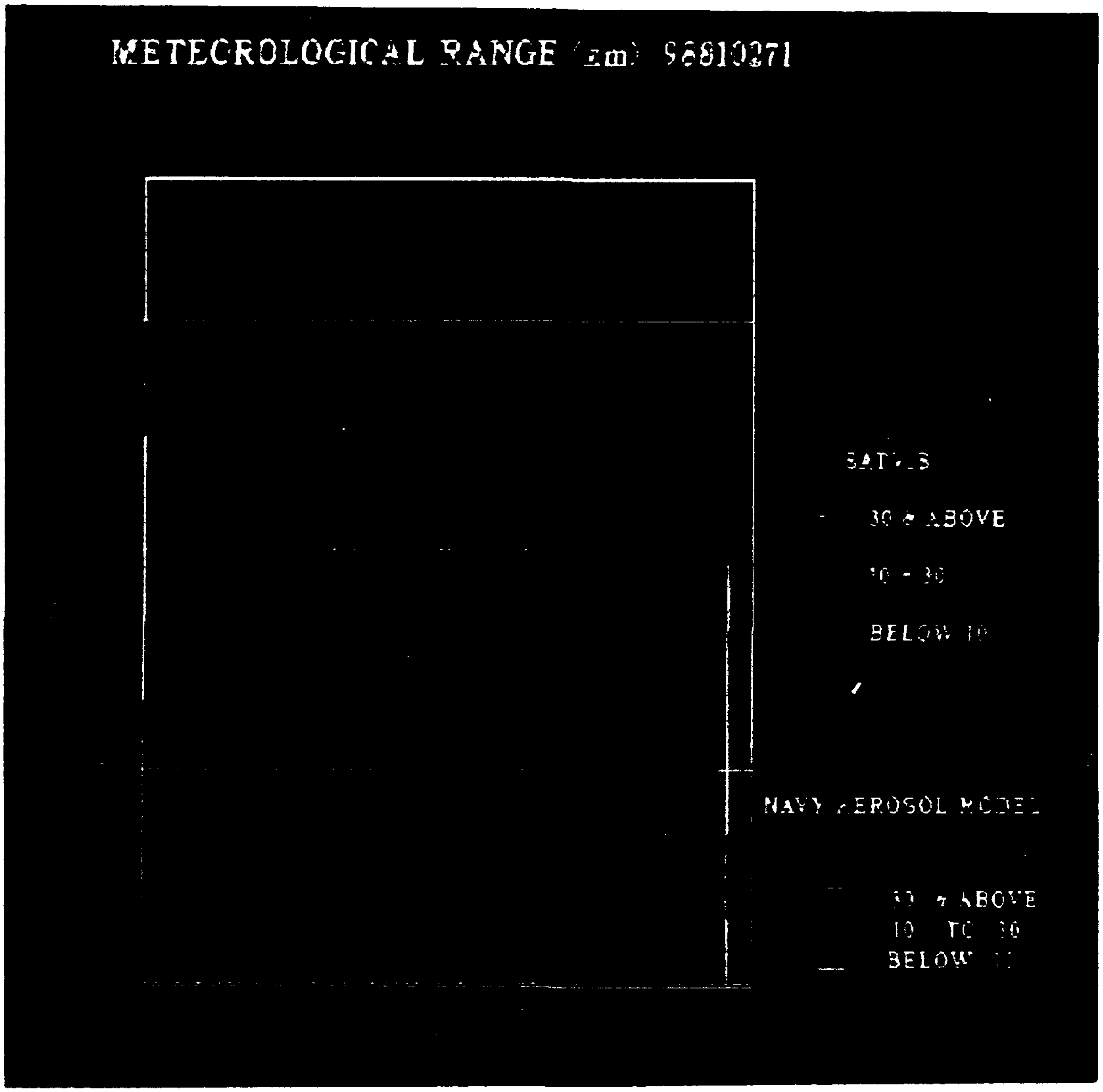

Figure 12: SATVIS and Navy Aerosol Model Ranges for 27 Oct 88. Ignore low values on extreme right of diagram.

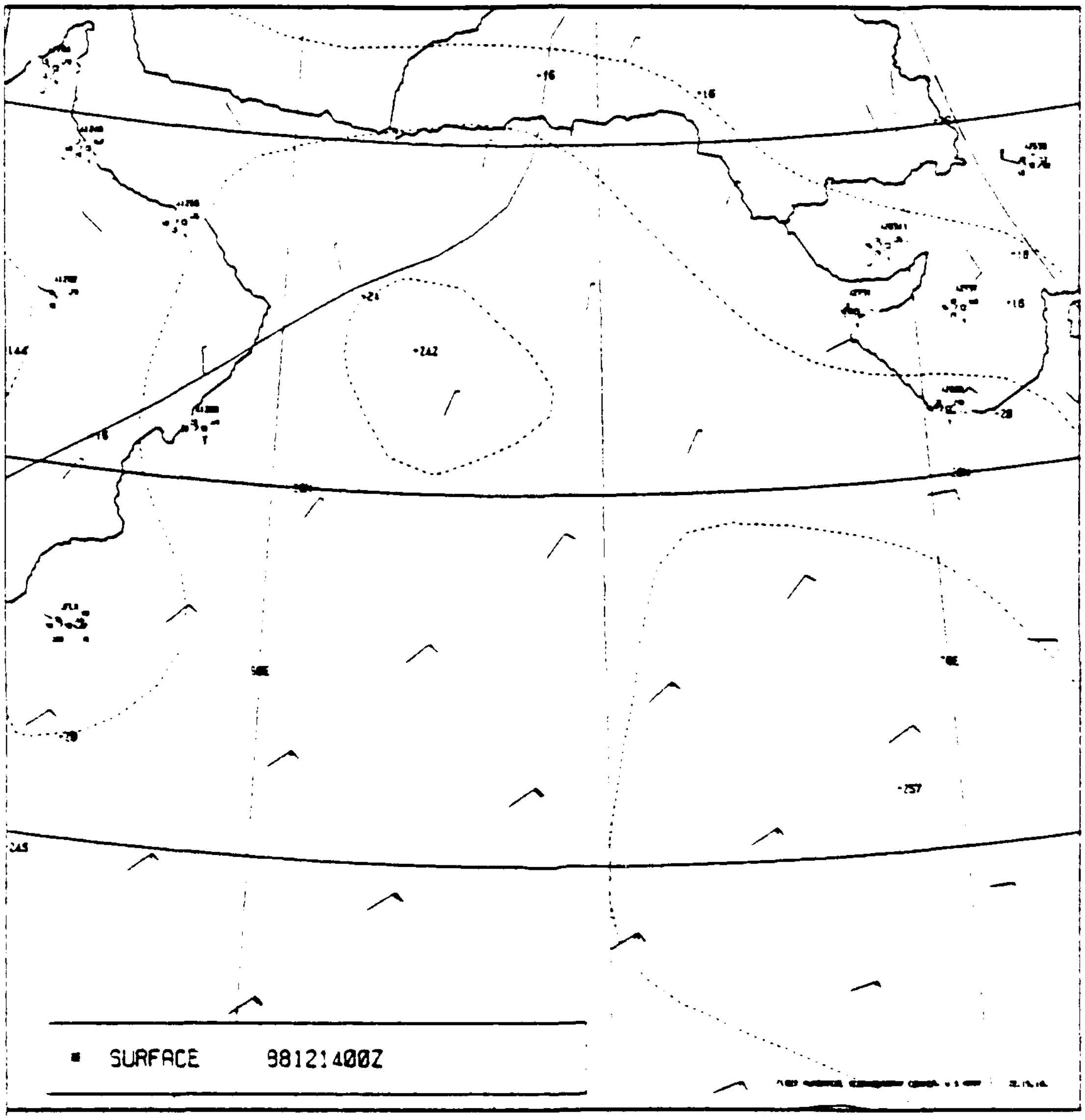

Figure 13: 00 UT 14 Dec 88 NOGAPS Surface OI Analysis.

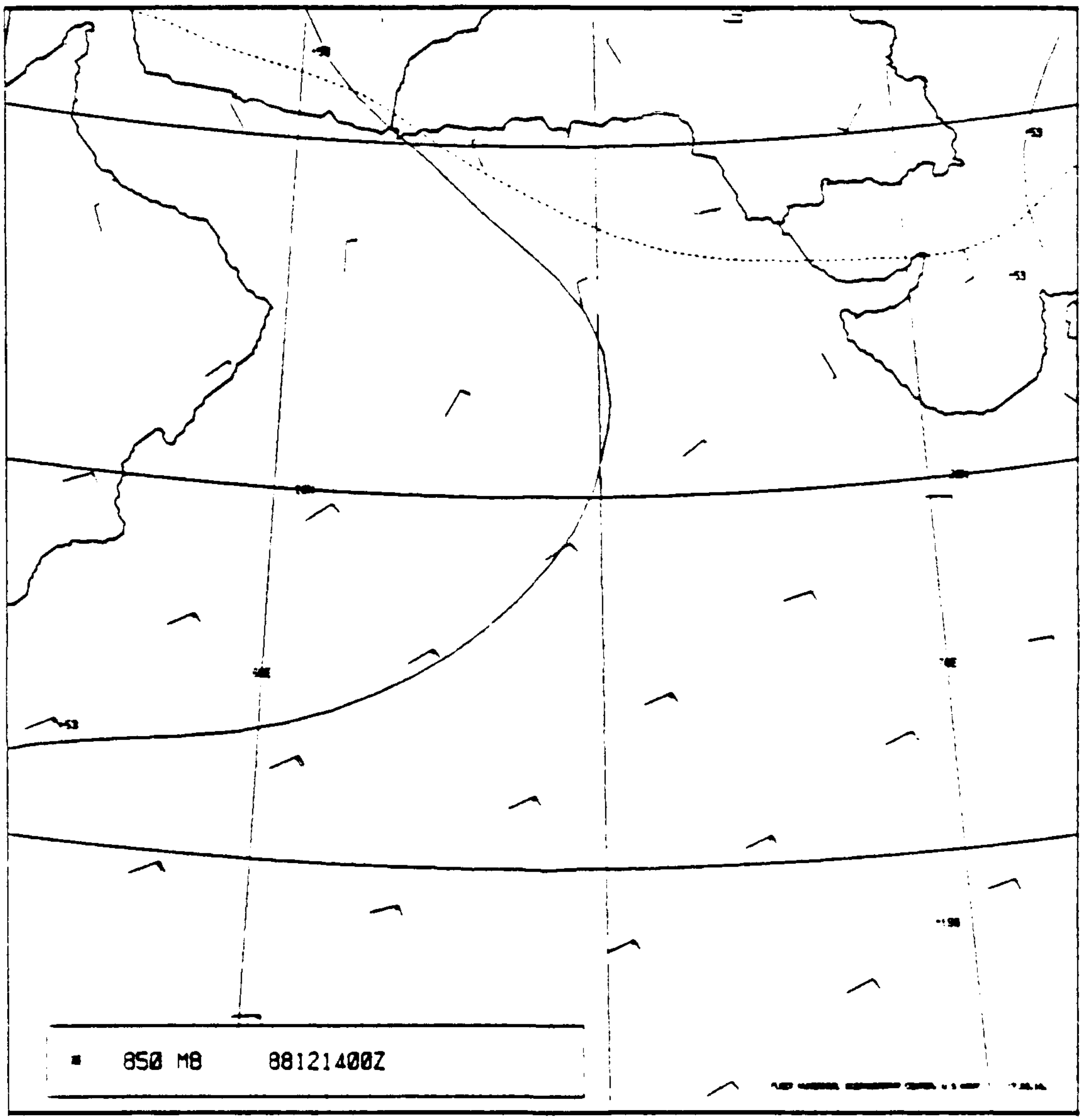

Figure 14: 00 UT 14 Dec 88 NOGAPS 850 mb OI Analysis.

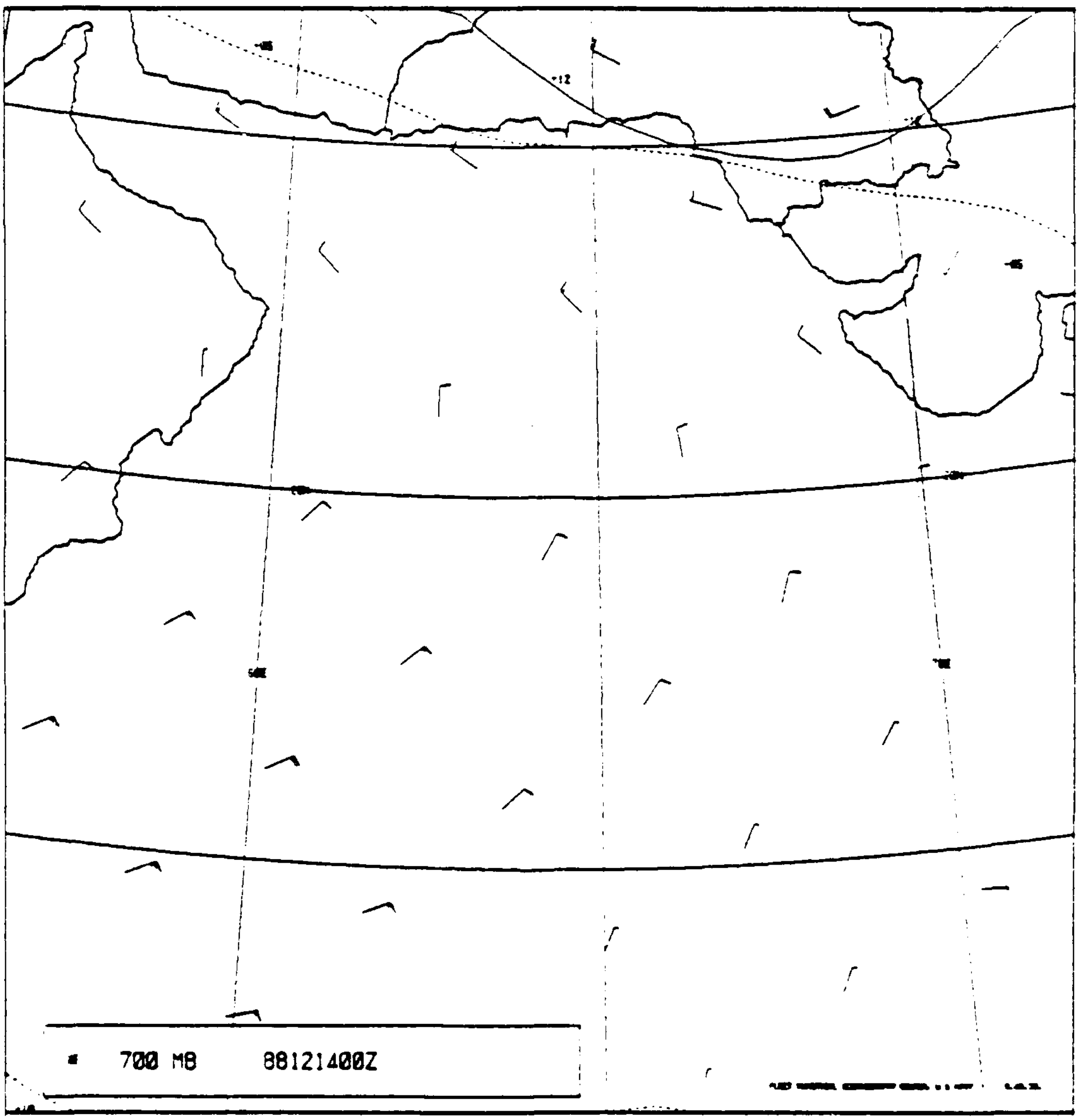

Figure 15: 00 UT 14 Dec 88 NOGAPS 700 mb OI Analysis.

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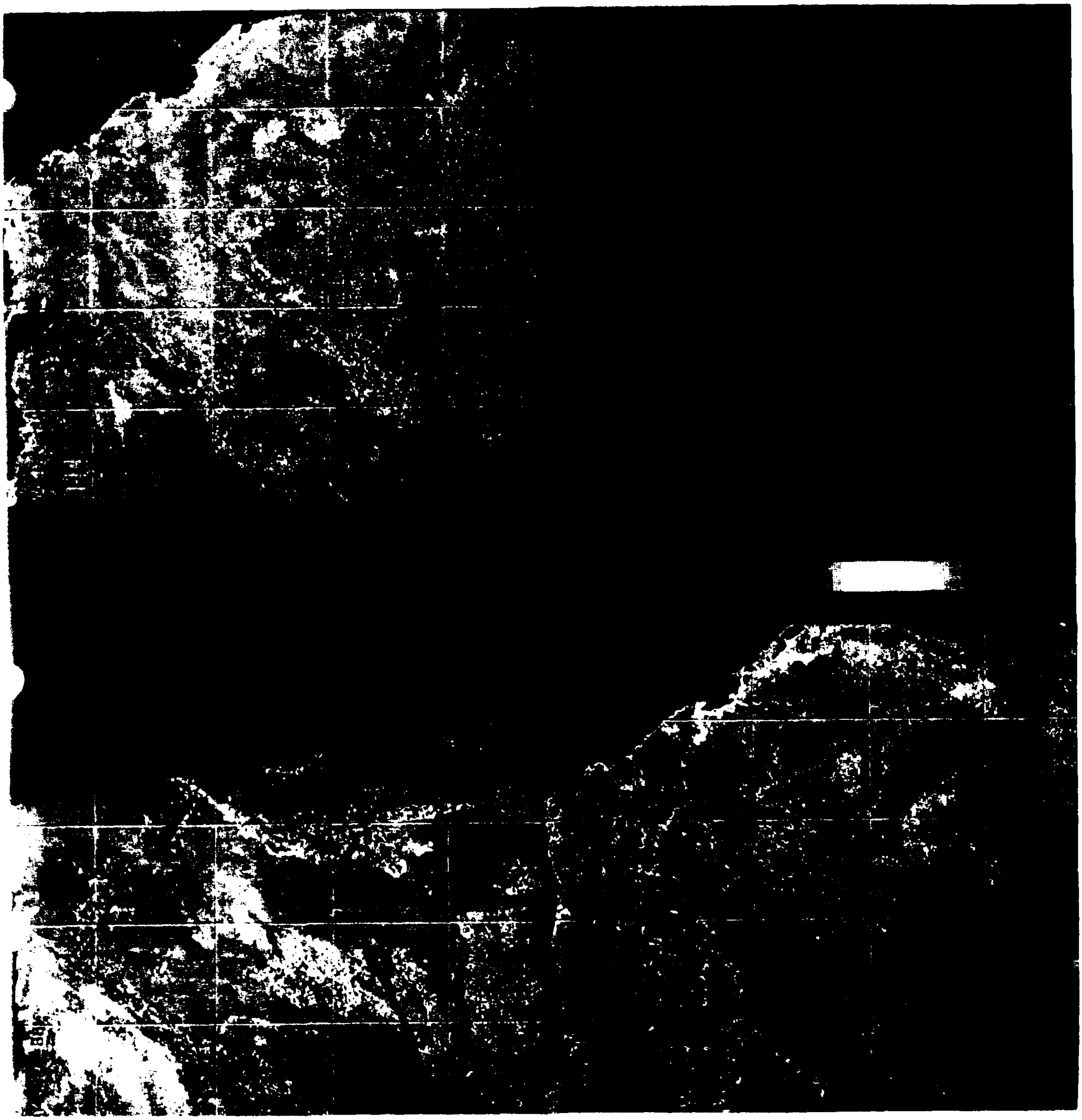

Figure 16: 14-16 Dec 88 SATVIS Optical Depth.

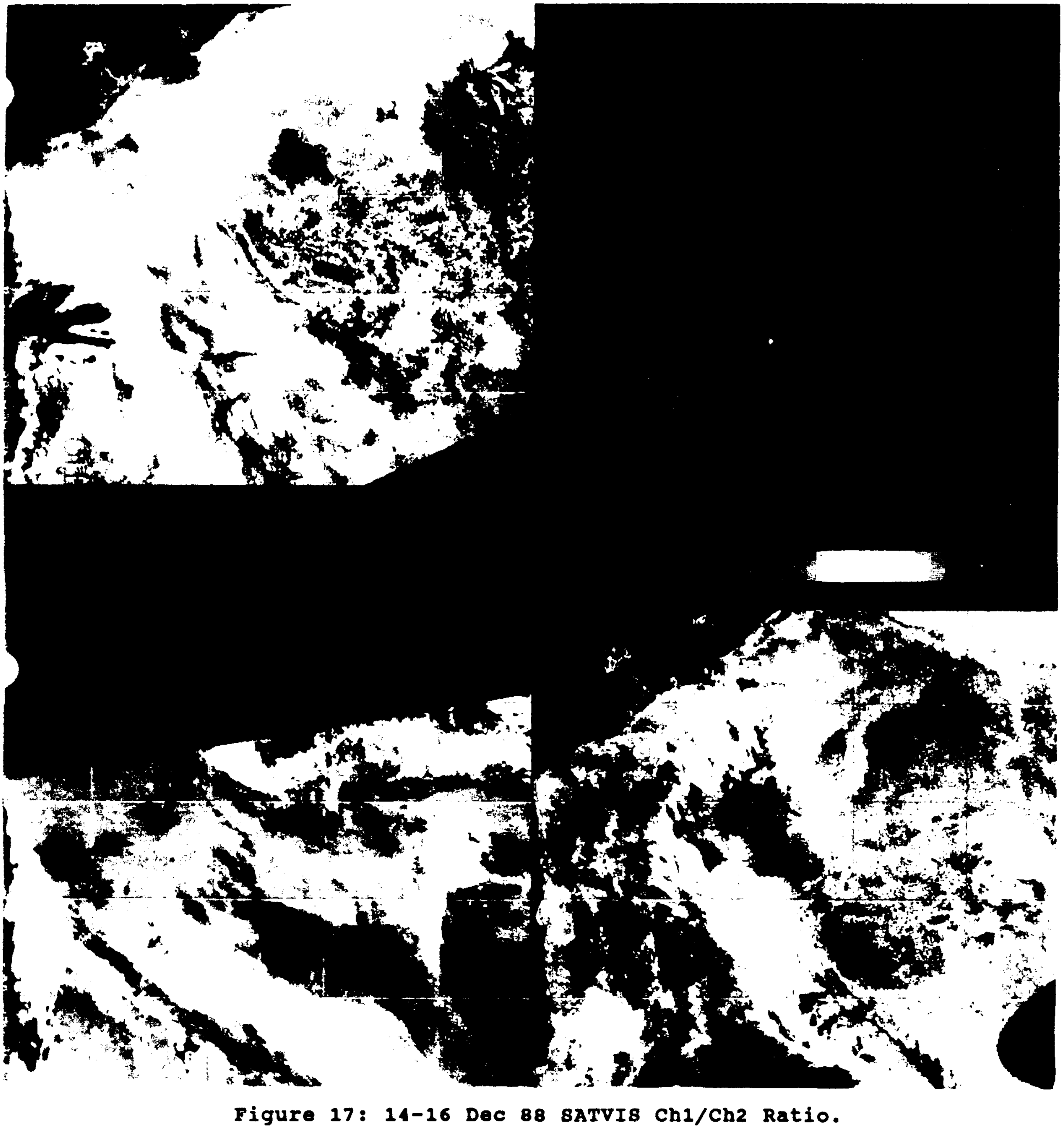

Figure 17: 14-16 Dec 88 SATVIS Ch1/Ch2 Ratio.

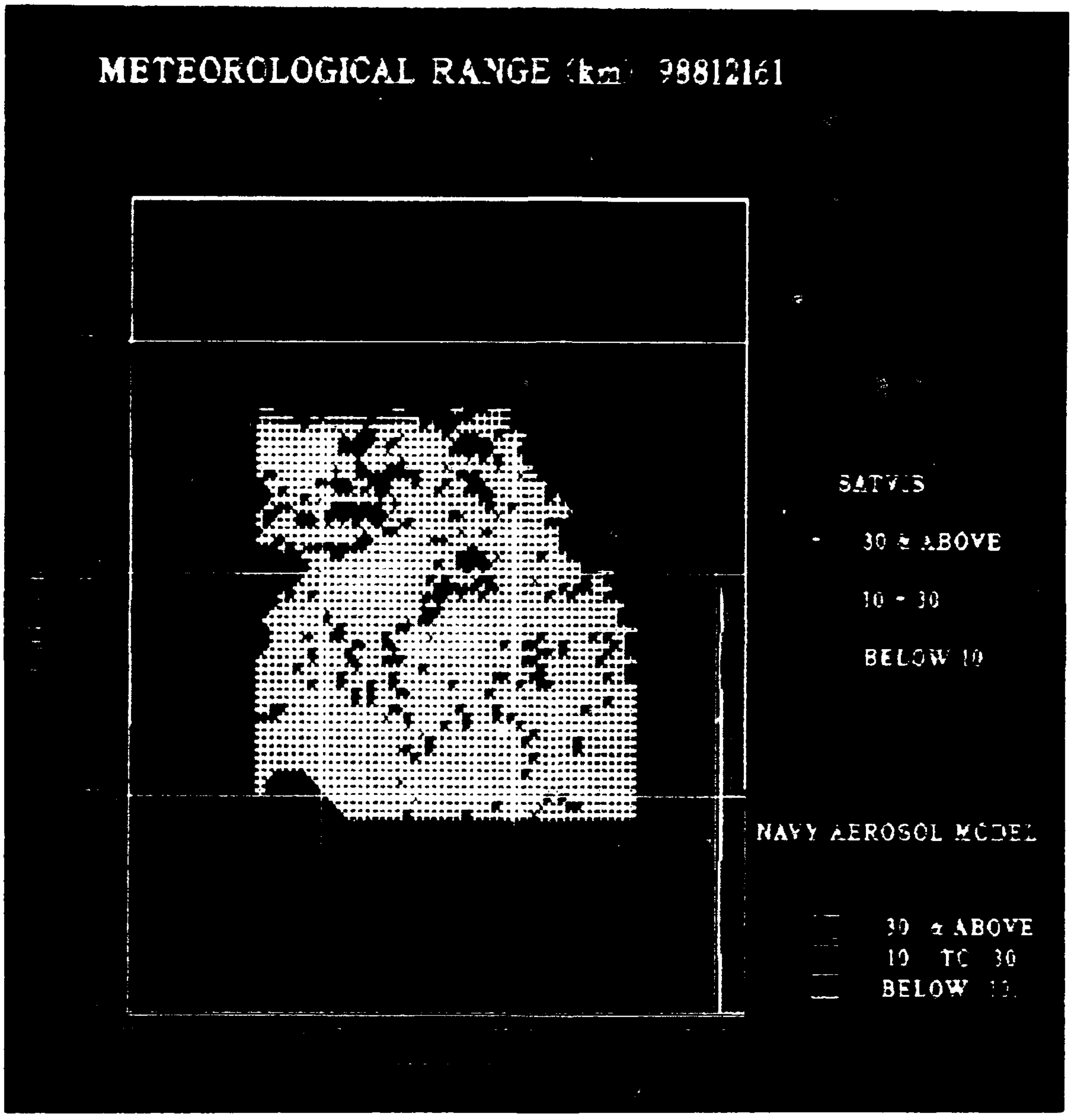

Figure 18: SATVIS and Navy Aerosol Model Ranges for 16 Dec 88. Ignore low values on extreme right of diagram.

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The Navy's SATVIS Meteorological Range Estimation Model is evaluated utilizing a subset of Advanced Very High Resolution Radiometer (AVHRR) data over the northern Arabian Sea during October 1988 through May 1989. Variations in aerosol optical depth and the ratio between AVHRR channels 1 and 2 are observed and correlated with synoptic data. SATVIS meteorological ranges are compared with those determined using the Navy Aerosol Model. Sources of error are discussed in light of recent observations of the vertical distribution of aerosols in the troposphere. A qualitative assessment of SATVIS as a Navy Tactical Decision Aid (TDA) is attempted.

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